



RESEARCH ARTICLE

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FAULT DETECTION AND CLASSIFICATION FOR COMPENSATED TRANSMISSION LINES WITH UPFC AND WIND FARM USING ARTIFICIAL INTELLIGENCE

Banumalar Koodalsamy^{1*} and Manikandan Bairavan Veerayan²

^{1,2}Mepco Schlenk Engineering College, Sivakasi, Tamil Nadu, India.

¹<https://orcid.org/0000-0003-4726-4620>, ²<https://orcid.org/0000-0002-6215-3729>

E-mail: *banumalar.234@gmail.com, bvmani@mepcoeng.ac.in

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ABSTRACT

The world is moving towards renewable energy source to be the major source to meet the increasing electricity demand and wind energy is one of the suitable sustainable energy sources. This brings the need to integrate large-scale wind farms with the existing power grids. Doubly fed induction generator (DFIG) are most preferred wind turbine generators with benefits like high efficiency and flexible power. However, DFIG is sensitive to grid disturbances and so traditional relaying protection techniques are not applicable. DFIG are integrated to the power grid with transmission line. Using UPFC compensated transmission lines increases the complexity further. The grid side current signals are extracted using Variable Mode Decomposition (VMD) method. These results in grayscale images which are then are used in convolutional neural network (CNN) classifier for fault classification. The simulation is done using 2021 version MATLAB simulink with 1300 fault data. There are a total of 10 cases of fault. The performance of the deployed CNN classifier is assessed with accuracy being 97.95 % for CNN.



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I. INTRODUCTION

The most commonly used wind turbine generator is doubly fed induction generator. DFIG is integrated with the power grid with transmission lines. DFIG despite its benefits like high efficiency and flexible power, it's susceptible to the grid disturbances. In order to transmit wind power generated in large scale to long distance, compensated transmission line is the most plausible option with the use of FACT devices [1],[2]. The FACT devices used frequently nowadays are UPFC as it has the ability for controlling active, reactive power capacity flow independently. When in comparison to the conventional synchronous machine, the DFIG due to its LVRT capability gives rise to certain fault nature [3]. Use of the UPFC adds to the rapid change in the impedance of the line [4]. So, the traditional Transmission Line protection techniques that are based on relay are not applicable to DFIG wind farm, that's connected to the UPFC compensated Transmission Line. In [5], discusses a novel 3 zone protection scheme. Here the zone 2 and zone 3 are not altered but zone 1 is altered from the conventional in order to not let the UPFC's impact affect the line for the separation of external and internal faults and uses line voltage.

The issues related to differential relay when applied in a DFIG wind farm and the added characteristic of DFIG during fault because of its response being fast is described in [6] and devices a solution to rectify this behavior which proves to be effective. However, the effect of DFIG on the fault detecting relaying scheme is not considered in this work. DFIG wind turbine generators are implemented with crowbar circuit to detect the LVRT at times of fault [7] and the method improved for the superimposed components-based distance protection gives sensitivity and proves to be reliable. A signal with the difference between two zero crossings and the local extreme numbers as one is known as a mode. VMD has been in used in several works such as in [8], analyzing the voltage flicker that varies with time which could be one of the often-addressed problems in power system. Modes numbered in several numbers decomposing the actual signal and help to make it into a constrained problem with variation and also introducing suitable Lagrange multiplier and quadratic term to generate an unconstrained problem as well.

In [9], CNN is been customized for fault classification in systems with distributed generators, which is a major task in relaying system and in order to clear the fault, it has to be done in a minimum amount of time. Here CNN has been applied to detect fault with voltage, current data (three-phase) which is just sampled and raw. And this method has been proved to be of better performance in comparison with traditional approaches. In [10], it paves way to a new self-attention CNN model that is used in transmission line fault to detect and classify faults. These faults are due to the system instability and might cause load damage. The noise elimination in the measured signals is carried out with the help of discrete wavelet transform. This proposed scheme results with high accuracy ensuring it as being a reliable method. The combination of VMD and CNN can be found effective to determine faults in machine that are rotating in nature. In [11-14], the diagnosis of fault, the optimized number of modes is determined. Analysis of the signal decomposed is analyzed by correlation and the reconstruction of the original signal is done by the selected components that are correlated highly. The 2-D desired features are mapped from the fault signal with the use of continuous Wavelet Transform. Next, in order to determine the desired fault features the 2-D images are deployed.

1.1 METHODOLOGY USED

The work flow is as below

- The DFIG wind farm connected to grid with the transmission line compensated with UPFC is simulated from 2021 version MATLAB simulink.
- The current data, voltage data and time data are extracted from the simulation with the voltage, current measurement devices connected at the grid side. The data extracted by creating 10 different fault cases as in Table 1.
- The extracted data is deployed with Variable Mode Decomposition to obtain the desirable features. Wiener filter is used so as to eliminate any noise present in the data and grey-scale as well as color images were generated.
- The grey-scale and color images have been fed for input in the CNN classifier and 1300 images are used for the training and testing.

Table 1: Fault Classes.

Fault Type	Fault
Single Line to Ground	AG, BG, CG
Line to Line	AB, BC, CA
Double Line to Ground	ABG,BCG,CAG
Line-Line-Line	ABC

Source: [9].

II. PROBLEM STATEMENT

The schematic model used in the current system is depicted in Figure 1. The system comprises a DFIG wind farm of capacity 9MW with six DFIG-WTG search of 1.5 MW capacities and are linked to a 25-kV distribution system that will export power to a grid (120-kV) via a 25-kV collector line. It is a 2-bus system with relays and breakers, one of each present on the wind side and the other on the grid side.

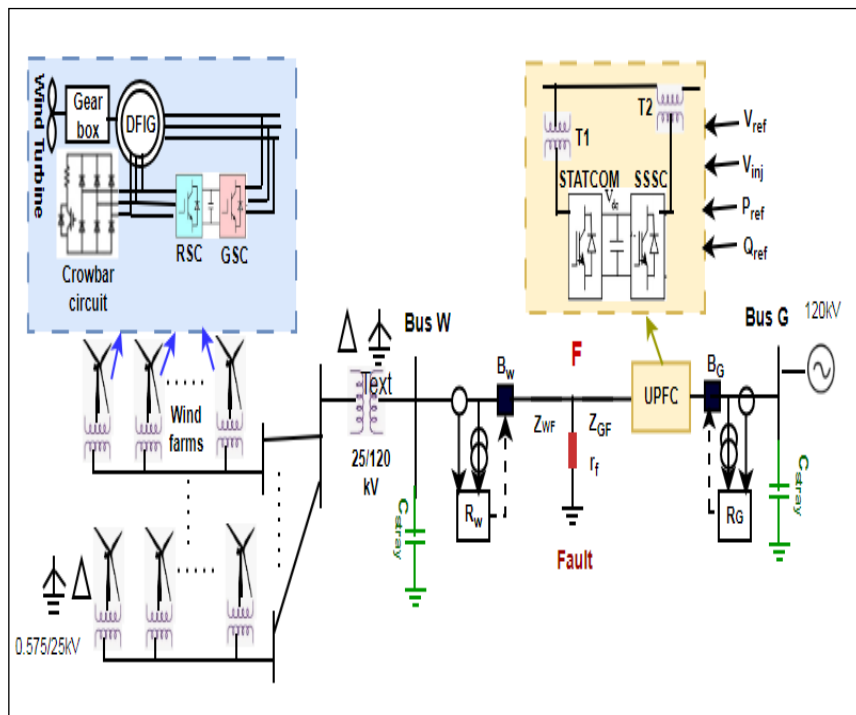


Figure 1: Schematic illustration of the DFIG - wind farm with UPFC-CTL.

Source: Authors, (2026).

The UPFC unit could be operated in four differing modes as:

1. Voltage Control Mode (VCM).
2. Voltage Injection Mode (VIM).
3. Power Flow Control Mode (PFM).
4. VAR Control Mode (VARCM).

The current, voltage and impedances of the wind side and grid side are denoted as E_{WT} , E_G , I_W , I_G and Z_W , Z_G , respectively. The impedances of the STATCOM and SSSC are represented by Z_{STAT} and Z_{SSSC} respectively. The current injected or absorbed by the STATCOM is I_{STAT} . The impedances of transmission Line are denoted as Z_{TL} . The V_W and V_G are the voltages at Bus-W and Bus-G respectively. The superscripts 'pre' and 'post' denotes parameters subjected to pre-fault and post fault respectively. At location x per unit a fault with a resistance of R_F value created from the Bus-W and fault current passes through it is I_f . By using Kirchoff's current law in Figure 2(b),

$$\Delta I_W = \frac{Z_{GU} + (1-x)Z_{TL}}{Z_{GU} + Z_{TL} + Z_W^{pf}} I_f \quad (1)$$

$$I_G = \frac{Z_W^{pf} + xZ_{TL}}{Z_{GU} + Z_{TL} + Z_W^{pf}} I_f \quad (2)$$

$$I_f = I_W^f + I_{SH}^f + I_G^f \quad (3)$$

$$\Delta I_W = I_f^w - I_W^{pre} \quad (4)$$

Equating (1) with (4),

$$\frac{Z_{GU} + (1-x)Z_{TL}}{Z_{GU} + Z_{TL} + Z_W^{pf}} I_f = I_W^f - I_W^{pre} \quad (5)$$

On substituting equation (3) in (5),

$$\frac{Z_{GU} + (1-x)Z_{TL}}{Z_{GU} + Z_{TL} + Z_W^{pf}} (I_W^f + I_{STAT}^f + I_G^f) = I_W^f - I_W^{pre} \quad (6)$$

On rearranging the equation,

$$Z_W^{pf} = \frac{(Z_{GU} + Z_{TL}(1-x))(I_{SH}^f + I_G^f) + (Z_{GU} + Z_{TL})(I_W^{pre} - Z_{TL}xI_W^f)}{I_W^f - I_W^{pre}} \quad (7)$$

$$\Delta I_G = I_G^f - I_G^{pre} \quad (8)$$

Equating (2) & (8) and I_f from equation (3)

$$\frac{Z_W^{pf} + xZ_{TL}}{Z_{GU} + Z_{TL} + Z_W^{pf}} I_f = I_G^f - I_G^{pre} \quad (9)$$

$$\frac{(Z_W^{pf} + xZ_{TL})}{(Z_{GU} + Z_{TL} + Z_W^{pf})} (I_W^f + I_{STAT}^f + I_G^f) = (I_G^f - I_G^{pre}) \quad (10)$$

$$Z_{GU} = \frac{[(Z_W^{pf} + xZ_{TL})(I_W^f + I_{STAT}^f + I_G^f)] - [(Z_{TL} + Z_W^{pf})(I_G^f - I_G^{pre})]}{(I_G^f - I_G^{pre})} \quad (11)$$

We know that,

$$Z_{GU} = \frac{(Z_{SSSC}^{pf} + Z_G^{pf})Z_{STAT}^{pf}}{Z_{SSSC}^{pf} + Z_G^{pf} + Z_{STAT}^{pf}} \quad (12)$$

Substituting equation (12) in (11), equation (13) is obtained,

$$Z_G^{pf} = \frac{Z_{STAT}^{pf}Z_{STAT}^{pf} - Z_{GU}(Z_{SSSC}^{pf} + Z_{STAT}^{pf})}{Z_{GU} - Z_{STAT}^{pf}} \quad (13)$$

Substituting Z_W^{pf} in Z_G^{pf} we get,

$$Z_G^{pf} = \frac{(Z_{STAT}^{pf} + Z_{SSSC}^{pf})[(Z_W^{pf} + xZ_{TL})(I_W^f + I_{STAT}^f)I_W^{pre} - (1-x)Z_{TL}I_G^f] - Z_{SSSC}^{pf}Z_{STAT}^{pf}(I_G^f + I_G^{pre})}{[Z_{STAT}^{pf} + (1-x)Z_{TL}]I_G^f - (Z_{STAT}^{pf} + Z_{TL} + Z_W^{pf})I_G^{pre} - (Z_W^{pf} + xZ_{TL})(I_W^f - I_{STAT}^f)} \quad (14)$$

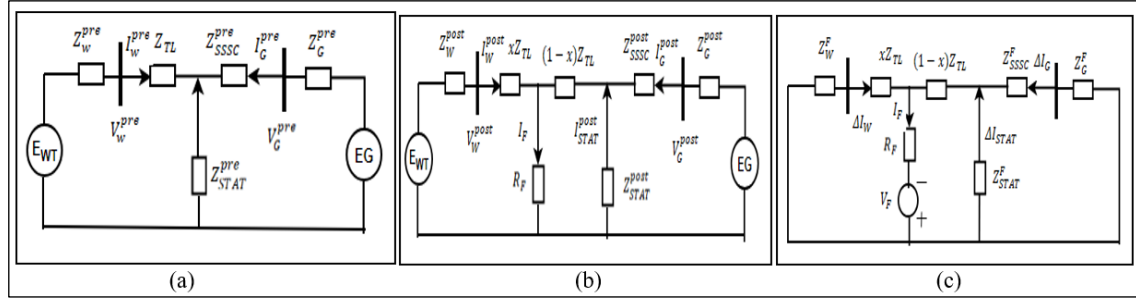


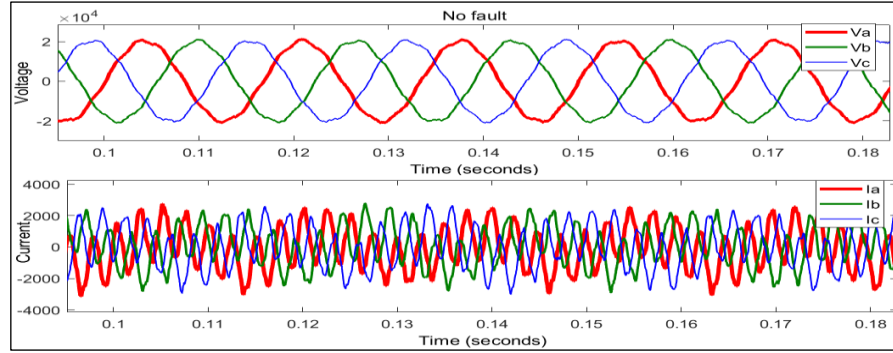
Figure 2: (a) Equivalent circuit a) pre fault b) post fault c) During fault.

Source: Authors, (2026).

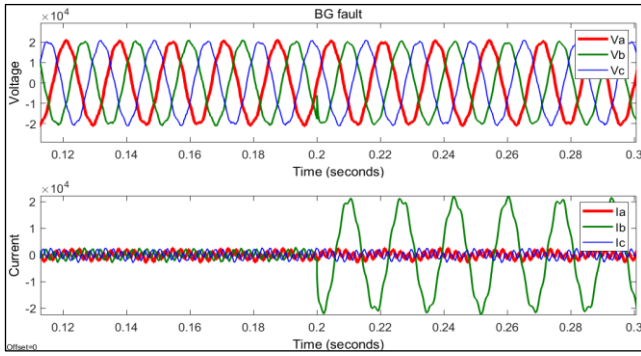
For a symmetrical fault the post fault impedances as from Equation (7) and (14), are influenced by the impedances of both UPFC and the DFIG-based wind farm.

II.1 DATA EXTRACTION AND PREPARATION

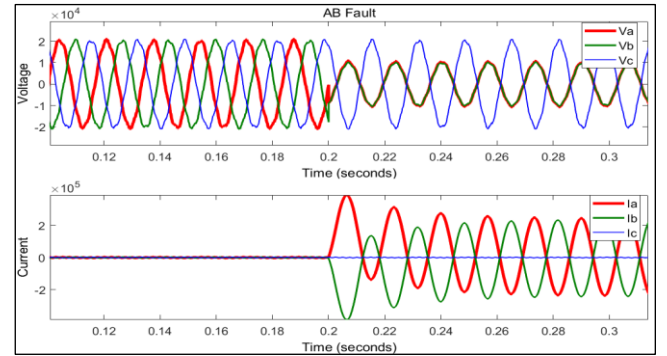
Using 2021 version MATLAB simulink model, the fault data are extracted and to understand the fault occurrence frequency, the waveforms are produced. The waveform displayed in Figure 3(a) showed is the standard sinusoidal voltage and current waveform. The graphs in Figure 3(b) to 3(e) show the waveforms that validate the existence of a fault in the system. The fault current and voltage data for different time were produced for deep-learning and its training to classify and find the point of faults in transmission line.



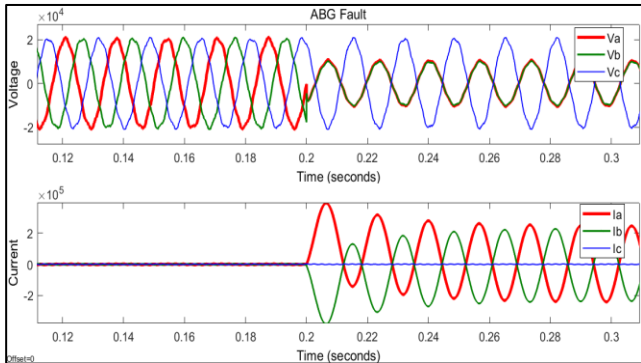
(a)



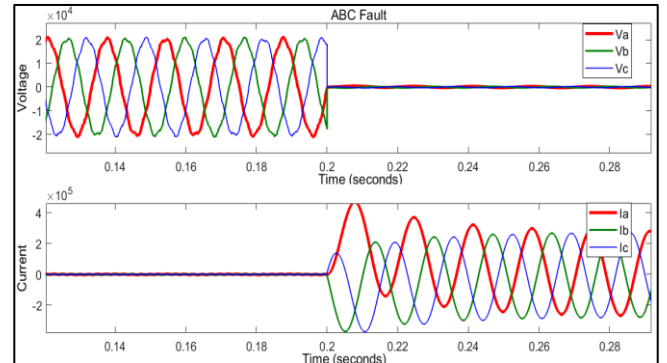
(b)



(c)



(d)



(e)

Figure 3: (a) Three phase in the absence of faults (b) B-G fault (c) A-B fault (d) A-B-G fault (e) A-B-C fault.

Source: Authors, (2026).

In Figure 3, five distinct scenarios of the system are shown namely, absence of faults, single-phase-to-ground fault, line-line fault, double-line-to-ground fault, and three-phase fault. V_a , V_b , V_c , and I_a , I_b , I_c represent the phase voltage and current respectively of each phase.

1. In the no-fault state, the waveform maintains sinusoidal integrity, free from any distortion caused by noise or faults as depicted in Figure 3(a).
2. In Figure 3(b) to 3(e), the voltage and current of phases are distorted with fault presence in the line and the waveforms depicts a distortion because of presence of these faults.
 - Figure 3(b) represents BG fault which is of SLG fault type, here the voltage profile and I_b are unaffected while I_a and I_c are reduced.
 - The next Figure 3(c) depicts AB fault which is of Line-Line fault type and here I_a and I_b are not affected while I_c becomes zero. Also, V_a and V_b are reduced and are in phase while V_c remains unaffected.
 - From Figure 3(d), it can be seen that in the presence of DLG fault (ABG), the current in the healthy phase C becomes zero while its voltage profile remains unaltered. And magnitude of V_a and V_b are reduced while the current of the faulty phase remain unchanged.
 - Figure 3(e) displays a three-phase fault and the voltage, current waveform of all the three phases V_a , V_b , V_c , and I_a , I_b , and I_c are distorted after the fault was introduced.

III. PROTECTION SCHEME

The wind side fault current has more complexities in comparison to the grid side [15]. Therefore, in order to overcome the complexities, grid side currents are used by the relaying protection approach to identify and categorize faults in the UPFC compensated transmission lines. The flowchart for the entire process is given in Figure 4 and accuracy calculated using Figure 5. When the occurrence of fault is identified, then via the power line communication carrier (PLCC), a trip signal travels towards the relay in the wind side. The PLCC faces with a communication delay of 5ms [15], however, fault current on the wind side is only 1.2 p.u., effectiveness of the relaying approach remains unaffected. There are two steps involved in the detection and classification of faults. First, the spectral energy ratio for the mode components of the grid side current is retrieved using VMD at a sampling frequency of 4 kHz. This could be applied to differentiate between defects that are internal and external. In the next stage, once the internal fault is detected, a combination of VMD and CNN Classifier is used for the classification of the faults.

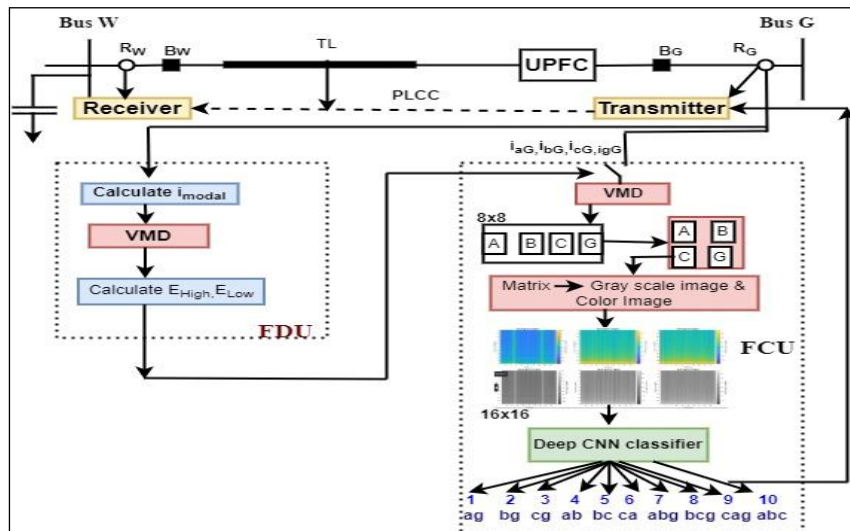


Figure 4: Flow chart for the entire process.

Source: Authors, (2026).

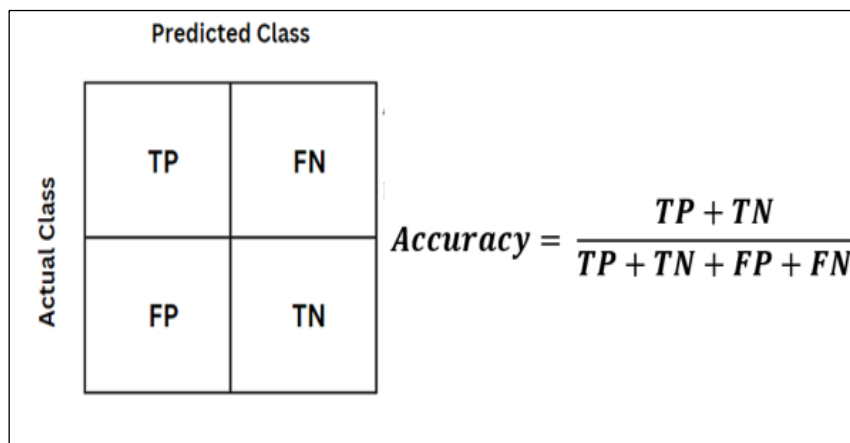


Figure 5: Confusion Matrix.

Source: [9].

IV. RESULTS AND DISCUSSIONS

Using MATLAB simulink, 1300 failure instances are created from IMFs to show the efficiency of the suggested relaying model by altering the system characteristics. The data were extracted at a sample frequency of 4 kHz for a 50 Hz power system. An 12th generation Intel Core i5 laptop with 16 GB RAM was used for current study.

IV.1 RESULTS OF VMD AND WIENER FILTER

In Figure 6, the extracted IMFs after decomposition are shown and the number of modes taken is 6. The signal is decomposed into six intrinsic mode functions. It can be seen that the extracted functions contain noise. The extracted IMFs are then filtered using Wiener Filter in order to eliminate the noise and the resulting filtered current signal is shown in Figure 7, which is Current and Time plot.

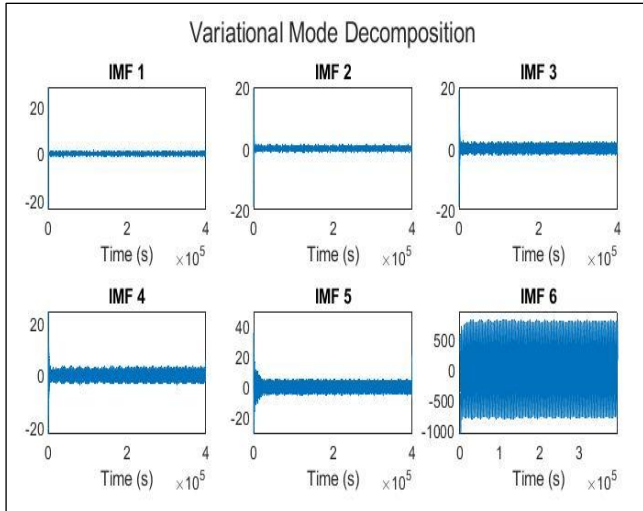


Figure 6: Decomposition using VMD: Extracted IMF.
Source: Authors, (2026).

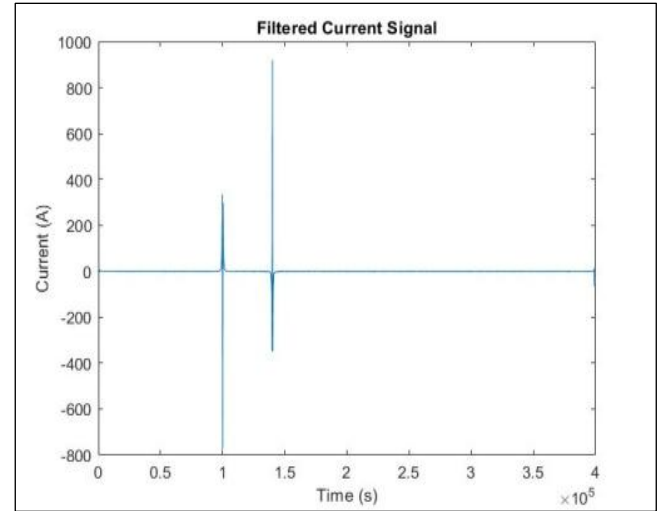


Figure 7: Wiener Filter.
Source: Authors, (2026).

IV.2 RESULTS OF VMD FOR CNN CLASSIFIER

VMD is used to produce the spectrogram of time frequency distribution for each of ten fault cases. Figure 8(a) shows the spectrogram of time frequency distribution for AG fault. From the Figure 8(a), it can be observed that the spectrogram of signal for A phase differs from that of the B and C phases due to the presence of AG Fault. From this it can be speculated that in case the fault that occurred is BG fault, then B phase differs from that of the A and C phases and according changes could be seen for each fault type. The data obtained from VMD are used in the generation of gray-scale images as in Figure 8(b) for each of the 10 different types of faults. These generated images are fed in to CNN classifier as input.

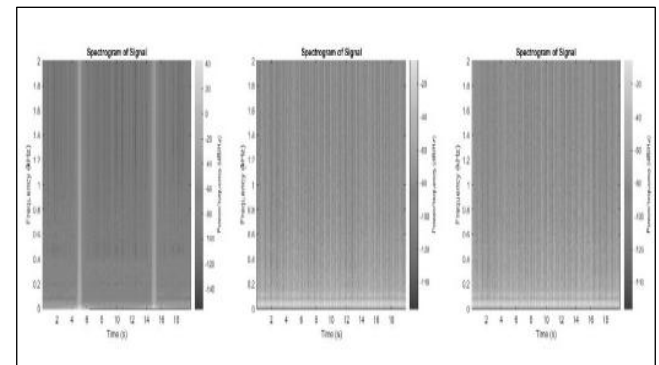
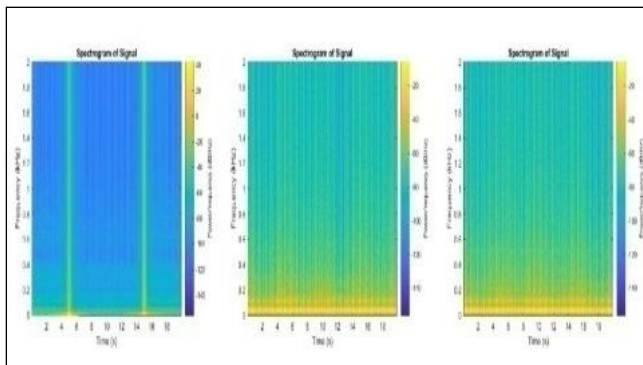
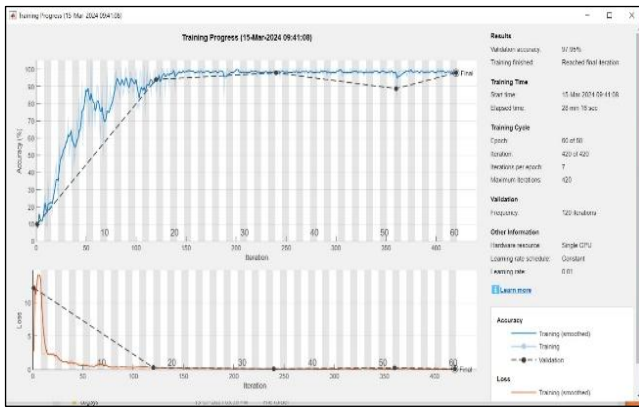


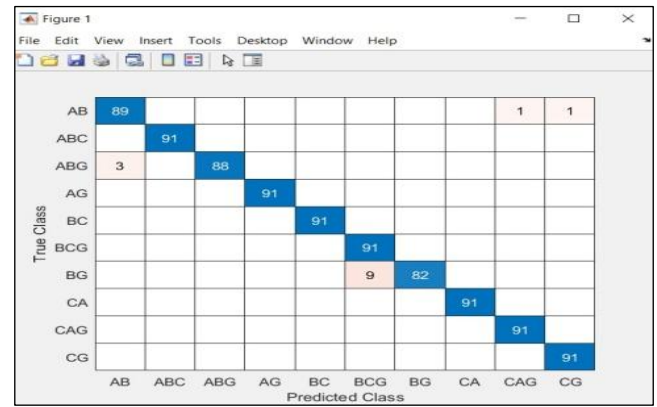
Figure 8: Spectrogram of time frequency distribution-AG Fault (a) Colored image (b) Gray-scale image.
Source: Authors, (2026).

IV.3 RESULTS OF CNN CLASSIFIER

Totally 1300 preprocessed gray-scale image data were used. Out of this 70% of the data, which are 910 images were used to train and the remaining 30% of the image data were used for testing. Maximum iterations are 420 with 60 epoch being carried out to train the data and 7 iterations per epoch. The elapsed time for running is 28 minutes 16 seconds. The performance curve of the CNN Classifier is shown in Figure 9(a) and Figure 10(a), it can be seen that by the end of the 60th epoch the curve gets saturated. Figure 9(b) and Figure 10(b) shows the confusion matrix generated by the CNN classifier for the relaying protection scheme used. From Figure 9 and 10, it can be seen that most of the faults have been correctly classified except for a few outliers due to misclassification. The validation accuracy of the CNN classifier for Gray scale and color image are 88% and 97.95%.

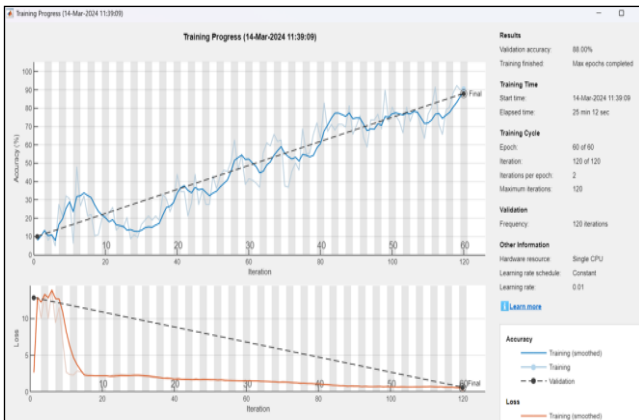


(a)

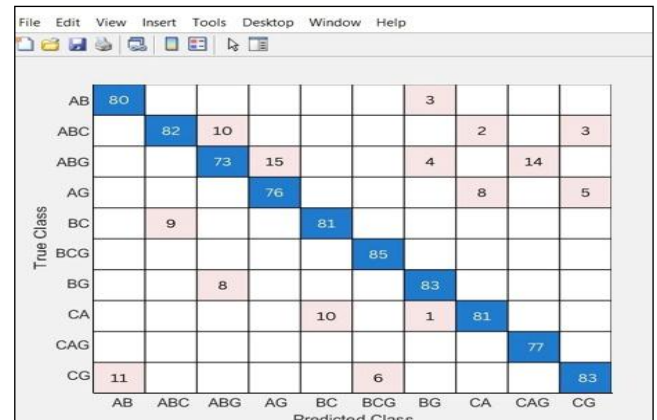


(b)

Figure 9: Color Image a) Performance Evaluation Curve b) Confusion Classifier.
Source: Authors, (2026).



(a)



(b)

Figure 10: Gray Scale Image a) Performance Evaluation Curve b) Confusion Classifier.
Source: Authors, (2026).

V. CONCLUSIONS

The protection system for grid connected DFIG based wind farm with UPFC-CTL was implemented with the combination of VMD-CNN is an intelligent method for identifying and categorizing transmission line defects. The MATLAB simulink model is simulated with the wind farm that consists of nine DFIG-WTGs. The system is used to detect and classify internal faults that could be both symmetrical and unsymmetrical faults using the grid side currents to reduce the complexity. The CNN classifier uses 70% and 30% of the 1300 processed images that are gray-scale in nature for training and testing respectively. From the performance curve, the accuracy obtained is 97.95% and proves to be better than most of the other existing approaches.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Banumalar Koodalsamy and Manikandan Bairavan Veerayan.

Methodology: Banumalar Koodalsamy and Manikandan Bairavan Veerayan.

Investigation: Banumalar Koodalsamy and Manikandan Bairavan Veerayan.

Discussion of results: Banumalar Koodalsamy and Manikandan Bairavan Veerayan.

Writing – Original Draft: Banumalar Koodalsamy.

Writing – Review and Editing: Banumalar Koodalsamy and Manikandan Bairavan Veerayan.

Resources: Banumalar Koodalsamy.

Supervision: Manikandan Bairavan Veerayan.

Approval of the final text: Manikandan Bairavan Veerayan.

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